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REDUCED CURRENT AND POWER CONSUMPTION STRUCTURE OF DRIVE CIRCUIT

BACKGROUND OF THE INVENTION

1 Technical Field of the Invention

The present invention relates generally to a drive circuit in which a high-side switching circuit and a low-side switching circuit are connected in series between power supply lines through an output terminal leading to a switching element to be controlled by the drive circuit, and more particularly to a reduced current and power consumption structure of such a drive circuit.

2 Background Art

Figs. 9 and 10 show a conventional drive circuit 1 designed to control an on-off operation of a switching element.

The drive circuit 1 is fabricated on an IC and designed to receive a control signal *Sa* inputted to an input terminal 2 to provide a drive voltage signal *Vo* to, for example, a gate of an *n*-channel MOSFET 4 coupled to an output terminal 3. The drive circuit 1 includes a high-side transistor *T1,* a low-side transistor *T2,* and a resistor *R1.* The high-side transistor *T1* and the low-side transistor *T2* are connected at collectors and emitters thereof in series between a positive power supply line 5 and a negative power supply line 6 (also referred to as a ground line 6 below) through the resistor *R1*. A junction of the resistor *R1* and the collector of the low-side transistor *T2* is coupled to the output terminal 3.

The drive circuit 1 also includes predrivers 7 and 8, a

transistor *T3*, and a constant current source *CS1*. The transistor *T3* is, as clearly shown in Fig. 10, disposed between the input terminal 2 and input terminals of the predrivers 7 and 8. The constant current source *CS1* works to provide a bias current to the transistor *T3*. The predrivers 7 and 8 receive a signal from the transistor *T3* to operate in logical forms reverse to each other and drive the transistors *T1* and *T2*, respectively.

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Specifically, the drive circuit 1 is a push-pull circuit which is responsive to the control signal *Sa* of a low level inputted to the input terminal 2 to turn on the transistor *T1* and off the transistors *T2* and *T3* so that the voltage *Vb* is applied from the power supply line 5 to the gate of the MOSFET *T4* to turn on the MOSFET *T4*. When the control signal *Sa* of a high level is inputted to the input terminal 2, the transistors *T2* and *T3* are turned on, while the transistor *T1* is turned off, so that the voltage of zero (0) at the ground line 6 is applied to the gate of the MOSFET *T4* to turn off the MOSFET *T4*.

Fig. 9 illustrates the structure of the drive circuit 1. The predrivers 7 and 8 have common elements for simplifying structures thereof. Specifically, the predrivers 7 and 8 are made up of the transistor *T4*, a transistor *T5*, a transistor *T6*, and resistors *R2* to *R8*. The transistor *T4* works to turn off the transistor *T1* and turns on the transistor *T2*. The transistor *T5* works to turn off the transistor *T2*. The transistor *T6* works to drive the transistor *T4*.

When the transistor *T3* is turned off by the control signal *Sa* of the low level, it will cause the transistors *T5* and *T6* to be turned on and the transistor *T4* to be turned off, so that the transistor *T1* is

turned on, and the transistor *T2* is turned off. Alternatively, when the transistor *T3* is turned on by the control signal *Sa* of the high level, it will cause the transistors *T5* and *T6* to be turned off and the transistor *T4* to be turned on, so that the transistor *T1* is turned off, and the transistor *T2* is turned on.

Between the gate and the source and between the gate and the drain of the MOSFET *T4*, capacitors *Cgs* and *Cgd* are usually provided, respectively. These gate capacitors are illustrated by broken lines in Fig. 10. Decreasing turning-on and -off time periods of the MOSFET *T4* to achieve a rapid switching operation thereof requires an increased ability of the drive circuit 1 to produce a great current for charging and discharging the gate capacitors of the MOSFET *T4* when required to be switched between the on-state and the off-state.

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Accordingly, in the drive circuit 1, the base current of the transistor *T2* is set to a great value for enabling the transistor *T2* to withdraw as the collector current thereof the electric charge from the gate capacitors for a short time when the MOSFET *T4* is switched from the on-state to the off-state. Additionally, the base current of the transistor *T1* is set to a great value for enabling the transistor *T1* to charge the gate capacitors of the MOSFET *T4* for a short time with the collector current thereof when the MOSFET *T4* is switched from the off-state to the on-state. The adjustment of these base currents are achieved by regulating the resistance values of the resistors *R4* and *R6*.

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The base current of the transistor *T2* inputted from the power

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supply line 5 through the resistor *R6* and the transistor *T4* continues to flow not only when the transistor *T2* is switched between the on- and off-states, but also during a steady-state operation in which the transistor *T2* is in the on-state (i.e., the MOSFET *T4* is in the off-state). An increase in base current of the transistor *T2* for shortening the turning-off time period thereof, thus, causes the current consumption of the drive circuit 1 to increase, which results in an increase in quantity of heat generated by the resistors *R4* and *R6*. This requires a decrease in guarantee ambient temperature of the IC in which the drive circuit 1.

In a case of a drive circuit (not shown) designed to drive a *p*-channel MOSFET, a great base current of a high-side transistor continues to flow when it is in the on-state for the same reasons as described above, thus resulting in an increase in energy loss of the drive circuit.

SUMMARY OF THE INVENTION

It is therefore a principal object of the invention to avoid the disadvantages of the prior art.

It is another object of the invention to provide a drive circuit whose the current and power consumption is decreased without sacrificing the switching speed of a switching element to be controlled by the drive circuit.

According to one aspect of the invention, there is provided a drive circuit for driving a switching element. The drive circuit comprises: (a) a high-side switching circuit connected between

power supply lines; (b) a low-side switching circuit connected in series with the high-side switching circuit through an output terminal leading to the switching element; and (c) a voltage detector detecting a voltage appearing at the output terminal. The low-side switching circuit is controlled to be turned off when the voltage detected by the voltage detector is lower than an off-decision voltage which is defined within a voltage range in which the switching element is in an off-state.

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In the preferred mode of the invention, the low-side switching circuit includes an output transistor, a predriver driving the output transistor, a comparing circuit comparing the output voltage detected by the voltage detector with the off-decision voltage, and a logic circuit controlling an operation of the predriver base on a result of comparison in the comparing circuit.

The comparing circuit includes a decision transistor having a control terminal into which the output voltage detected by the voltage detector is inputted.

The voltage detector is implemented by a voltage divider made up of resistors.

According to the second aspect of the invention, there is provided a drive circuit for driving a switching element which comprises: (a) a high-side switching circuit connected between power supply lines; (b) a low-side switching circuit connected in series with the high-side switching circuit through an output terminal leading to the switching element; and (c) a voltage detector detecting a voltage appearing at the output terminal. The high-side

switching circuit is turned off when the voltage detected by the voltage detector is higher than an on-decision voltage which is defined within a voltage range in which the switching element is in an on-state.

In the preferred mode of the invention, the high-side switching circuit includes an output transistor, a predriver driving the output transistor, a comparing circuit comparing the output voltage detected by the voltage detector with the on-decision voltage, and a logic circuit controlling an operation of the predriver base on a result of comparison in the comparing circuit.

The comparing circuit includes a decision transistor having a control terminal into which the output voltage detected by the voltage detector is inputted.

The voltage detector is implemented by a voltage divider made up of resistors.

According to the third aspect of the invention, there is provided a drive circuit for driving a switching element which comprises: (a) a high-side switching circuit connected between power supply lines; (b) a low-side switching circuit connected in series with the high-side switching circuit through an output terminal leading to the switching element; and (c) a voltage detector detecting a voltage appearing at the output terminal. The low-side switching circuit is turned off when the voltage detected by the voltage detector is lower than an off-decision voltage which is defined within a voltage range in which the switching element is turned off. The high-side switching circuit is turned off when the

voltage detected by the voltage detector is higher than an on-decision voltage which is defined within a voltage range in which the switching element is turned on.

In the preferred mode of the invention, the low-side switching circuit includes an output transistor, a predriver driving the output transistor, a comparing circuit comparing the output voltage detected by the voltage detector with the off-decision voltage, and a logic circuit controlling an operation of the predriver base on a result of comparison in the comparing circuit.

The high-side switching circuit includes an output transistor, a predriver driving the output transistor, a comparing circuit comparing the output voltage detected by the voltage detector with the on-decision voltage, and a logic circuit controlling an operation of the predriver base on a result of comparison in the comparing circuit.

The comparing circuit includes a decision transistor having a control terminal into which the output voltage detected by the voltage detector is inputted.

The voltage detector is implemented by a voltage divider made up of resistors.

~~BRIEF DESPCRIPTION OF THE DRAWINGS~~

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The present invention will be understood more fully from the detailed description given hereinbelow and from the accompanying drawings of the preferred embodiments of the invention, which, however, should not be taken to limit the invention to the specific

embodiments but are for the purpose of explanation and understanding only.

In the drawings:

Fig. 1 is a circuit diagram which shows a structure of a drive circuit according to the first embodiment of the invention;

Fig. 2 is a block diagram which shows a multi-channel driver equipped with a plurality of drive circuits equivalent to the one shown in Fig. 1;

Fig. 3 is a graph which shows a change in current consumption as a function of a change in level of a control signal *Sa* in the drive circuit shown in Fig. 1;

Fig. 4 is a graph which shows a change in current consumption as a function of a change in level of a control signal *Sa* in a conventional drive circuit shown in Fig. 9;

Fig. 5 is a circuit diagram which shows a structure of a drive circuit according to the second embodiment of the invention;

Fig. 6 is a block diagram which shows the drive circuit of Fig. 5;

Fig. 7 is a block diagram which shows a drive circuit according to the third embodiment of the invention;

Fig. 8 is a block diagram which shows a comparator which may be employed in the drive circuit of Fig. 1;

Fig. 9 is a circuit diagram which shows a structure of a conventional drive circuit according to the second embodiment of the invention; and

Fig. 10 is a block diagram which shows the drive circuit of Fig.

9.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

Referring to the drawings, wherein like reference numbers refer to like parts in several views, particularly to Figs. 1 to 4, there is shown a multi-channel driver according to the first embodiment of the invention.

Fig. 2 illustrates, as an example, a schematic circuit structure of a six-channel driver made up of six drive circuits 11. The following discussion will refer to, as an example, a case of use in engine control for automotive vehicles. The six drive circuits 11 are fabricated in one IC together with other circuits.

Each of the drive circuits 11 is designed to receive a control signal *Sa* inputted to an input terminal 12 of the IC in which the drive circuits 11 are fabricated from a CPU (not shown) to provide a drive voltage signal *Vo* to a gate of an *n*-channel MOSFET 14 through an output terminal 13 of the IC.

Between a drain of the MOSFET 14 and a positive terminal of a battery (i.e., a dc power supply) installed in the vehicle, an electric load such as a solenoid (not shown) is disposed. A source of the MOSFET 14 is coupled to a ground line 15 leading to a negative terminal of the battery. Capacitors *Cgs* and *Cgd* are provided inherently between the gate and the source and between the gate and the drain of the MOSFET 14, which are illustrated equivalently in Fig. 2 by broken lines.

A positive power supply line 16 and a negative power supply

line 17 (referred to as a ground line below) are coupled to the battery through an ignition switch (not shown), so that a power supply voltage (e.g., 14V) is developed therebetween. Between the power supply line 16 and the ground line 17, a collector and an emitter of an *npn* transistor *T11*, a resistor *R11*, and a collector and an emitter of an NPN transistor *T12* are connected. A junction of the resistor *R11* and the collector of the transistor *T12* is coupled to the output terminal 13. The transistors *T11* and *T12* work as a high-side transistor and a low-side transistor, respectively.

~~The drive circuit 11 includes an output control circuit 18 for driving the transistor *T11*, an output control circuit 19 for driving the transistor *T12*, an *npn* transistor *T13* disposed between the input terminal 12 and an input terminal of each of the output control circuits 17 and 18, a constant current source *CS11*, and a voltage detector 20. The voltage detector 20 is disposed between the output terminal 13 and the ground line 17 and works to detect the voltage (i.e., the voltage signal *Vo*) appearing at the output terminal 13. The transistor *T11* and the output control circuit 18 function as a high-side switching circuit. The transistor *T12* and the output control circuit 19 function as a low-side switching circuit.~~

Fig. 1 illustrates the details of the structure of the drive circuit 11.

The drive circuit 11 includes a logic circuit 21 and a comparator 22. The logic circuit 21 consists of constant current sources *CS12* and *CS14-CS17*, *npn* transistors *T14, T15,* and *T17-T20,* and resistors *R12-R17*. The comparator 22 consists of a

constant current source *CS13* and an *npn* transistor *T16* serving as a decision transistor.

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The drive circuit 11 also includes a high-side predriver 23 and a low-side predriver 24. The predriver 23 consists of a *pnp* transistor *T22*, *npn* transistors *T22* and *T23*, and resistors *R18* to *R20*. The predriver 24 consists of a *pnp* transistor *T24*, *npn* transistors *T25* and *T26*, and resistors *R21* to *R24*.

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The output control circuit 18 shown in Fig. 2 includes the logic circuit 21 and the predriver 22. The output control circuit 19 shown in Fig. 2 includes the logic circuit 21, the comparator 22, and the predriver 24. Specifically, the logic circuit 21 is used both in the output control circuits 18 and 19.

In the logic circuit 21, the transistors *T14* and *T15* are coupled at collectors and emitters thereof in parallel to the constant current source *CS12* and the ground line 17. The transistors *T17* to *T20* are coupled at collectors and emitters thereof to the constant current sources *CS14* to *CS17* and the ground line 17, respectively. The transistors *T14*, *T17*, and *T18* are coupled at bases thereof to the collector of the transistor *T13* through the resistors *R13*, *R14*, and *R15*, respectively. The transistors *T19* and *T20* are coupled at bases thereof to the collector of the transistor *T18* through the resistors *R16* and *R17*, respectively The transistor *T15* is coupled at the base thereof to the collector of the transistor *T16*.

In the predriver 23, the resistors *R18* and *R19* and an emitter and a collector of the transistor *T22* are coupled in series between the power supply line 16 and the ground line 17. An emitter and a

collector of the transistor *T21*, the resistor *R20*, and a collector and an emitter of the transistor *T23* are coupled in series between the power supply line 16 and the ground line 17. The transistors *T21*, *T22*, and *T23* are coupled at bases thereof to a junction of the resistors *R18* and *R19*, the collector of the transistor *T20*, and the collector of the transistor *T17*, respectively. The transistor *T23* is coupled at the collector thereof to the base of the transistor *T11*.

In the predriver 24, the resistors *R21* and *R22* and a collector and an emitter of the transistor *T25* are coupled in series between the power supply line 16 and the ground line 17. An emitter and a collector of the transistor *T24*, the resistor *R23*, and a collector and an emitter of the transistor *T26* are coupled in series between the power supply line 16 and the ground line 17. The transistors *T24*, *T25*, and *T26* are coupled at bases thereof to a junction of the resistors *R21* and *R22*, the collectors of the transistors *T14* and *T15*, and the collector of the transistor *T19*, respectively. The resistor *R24* is coupled to the base and emitter of the transistor *T12*.

The voltage detector 20 is implemented by a voltage divider consisting of resistors *R25* and *R26* connected in series between the output terminal 13 and the ground line 17. The voltage detector 20 works to produce an output voltage *Vp* as a function of the output voltage *Vo* appearing at the output terminal 13 and applies it to the base of the transistor *T16* through the resistor *R27*. The output voltage *Vp* is expressed by an equation below.

$$Vp = R26 / (R25 + R26) \cdot Vo \tag{1}$$

Where *R25* and *R26* indicate resistance values of the resistors *R25* and *R26*, respectively. In the following discussion, resistance values of the resistors *R11* to *R27* will also be expressed by *R11* to *R27*, respectively.

In this embodiment, in order to decrease the current flowing through the voltage detector 20, $R25 = 1\mathrm{k}\Omega$, and $R26 = 100\mathrm{k}\Omega$. The output voltage *Vp* may be expressed in the following close approximation.

$$Vp = Vo \tag{2}$$

The operation of the drive circuit 11 will be described below with reference to Figs. 3 and 4.

First, an operation of the drive circuit 11 during a change in level of the control signal *Sa* inputted to the input terminal 12 will be discussed. In the following discussion, "L-level" indicates a voltage level (e.g., 0V) lower than the base-to-emitter voltage *Vf* (about 0.7V) of a transistor, e.g., the transistor *T13*, and "H-level" indicates a voltage level higher than or equal to the voltage *Vf*. The control signal *Sa* is an H-level pulse signal whose pulse spacing is, for example, 4ms and pulse width is 200 to 400 μs.

(1) When the control signal *Sa* is changed from the H-level to the L-level

A change in level of the control signal *Sa* from the H-level to the L-level causes the transistor *T13* to be turned off, the transistors

T14, T17, and *T18* to be turned on, and the transistors *T19* and *T20* to be turned off. The turning on of the transistor *T14* causes the collector voltage of the transistors *T14* and *T15* to be changed to the L-level regardless of the level of the output voltage *Vp*.

The above operation of the logical circuit 21 causes, on the high side, the transistor *T22* to be turned on, the transistor *T23* to be turned off, and the transistors *T21* and *T11* to be turned on, while it causes, on the low side, the transistor *T25* to be turned off, the transistor *T26* to be turned on, and the transistors *T24* and *T12* to be turned off.

Specifically, when the control signal *Sa* is decreased in level, the drive circuit 11 supplies a charging current from the power supply line 16 through the transistor *T11*, the resistor *R11*, and the output terminal 13 to the gate capacitors of the MOSFET 14. This causes the gate of the MOSFET 14 to be activated so that the output voltage *Vo* to rise rapidly from 0V to a level substantially equal to the voltage *Vb* appearing at the power supply line 16 When the output voltage *Vo* exceeds a threshold value *Vth* of the MOSFET 14, it will cause the MOSFET 14 to be turned on.

(2) When the controls signal *Sa* is changed from the L-level to the H-level

An increase in level of the control signal *Sa* from the L-level to the H-level causes the transistor *T13* to be turned on, the transistors *T14, T17,* and *T18* to be turned off, and the transistors *T19* and *T20* to be turned on. This causes, on the high side, the transistor *T22* to be turned off, the transistor *T23* to be turned on, and the transistors

T21 and *T11* to be turned off. The collector voltage of the transistors *T14* and *T15*, i.e., the on-off state of the transistors *T24*, *T25*, and *T12* on the low side depend upon the level of the output voltage *Vo*.

Specifically, during a time when the output voltage *Vo* meets a relation, as shown below, after the control signal *Sa* is increased to the H-level, the transistor *T16* is in the on-state, so that the transistor *T15* is in the off-state.

$$Vo \geqq (R25 + R26) / R26 \cdot Vf \tag{3}$$

During the above time period, the collector of the transistors *T14* and *T15* is in the H-level, thereby causing the transistor *T25* to be turned on, the transistor *T26* to be turned off, and the transistors *T24* and *T12* to be turned on.

Thus, the drive circuit 11 works to discharge the electric charge on the gate capacitors of the MOSFET 14 to the ground line 17 through the output terminal 13 and the transistor *T12*. This causes the output voltage *Vo* to decrease from the level substantially equal to the voltage *Vb* rapidly. When the output voltage *Vo* drops below the threshold value *Vth* of the MOSFET 14, it will cause the MOSFET 14 to be turned off.

After the MOSFET 14 is turned off, when the output voltage *Vo* drops further and meets a relation, as shown below, it will cause the transistor *T16* to be turned off, so that the transistor *T15* is turned on.

$$Vo < (R25 + R26) / R26 \cdot Vf \quad (4)$$

Note that the voltage level defined by the right side of Eq. (4) is the level of an off-decision voltage which is set lower than the threshold value *Vth* of the MOSFET 14.

When the transistor *T16* is turned off (i.e., the transistor *T15* is turned on), the transistor *T25* on the low side is changed from the on-state to the off-state, thus causing the transistors *T24* and *T12* to be changed from the on-state to the off-state.

Specifically, at least during a change in level of the control signal *Sa* from the L-level to the H-level when the MOSFET 14 is switched from the on-state to the off-state, the transistor *T12* on the low side is turned on, thereby causing the electric charge to be removed quickly from the gate capacitors of the MOSFET 14. When the MOSFET 14 is in the off-state, and Eq. (4) is met, the transistor *T12* on the low side is turned off in addition to the transistor *T11* on the high side.

The resistors *R25* and *R26* making up the voltage detector 20 work as pull-down resistors acting on the gate of the MOSFET 14. Thus, even when both the transistors *T11* and *T12* are turned off, the gate of the MOSFET 14 is not brought into the high-impedance state. If the gate voltage of the MOSFET 14 is elevated over the off-decision voltage due to input of electric noises, it will cause the transistor *T12* on the low side to be turned on to decrease the gate voltage of the MOSFET 14, thereby preventing the MOSFET 14 from

being turned on in error.

Current and power consumptions of the drive circuit 11 of this embodiment and the drive circuit 1, as discussed in the introductory part of this application with reference to Fig. 9, when the control signal *Sa* is in the H-level will be indicated below.

(a) Drive Circuit 11

A decrease in current consumption by turning off of the transistor *T12* on the low side is

$$(Vb - V_{BE}(T24) - V_{CE}(T25)) / R22 + (Vb - V_{BE}(T12) - V_{CE}(T24)) / R23 + V_{BE}(T24) / R21 \qquad (5)$$

The current and power consumptions when the transistor *T12* is in the off-state are given by Eqs. (6) and (7) below.

$$\text{Current Consumption} = 7 \cdot I_{CS} \qquad (6)$$

$$\text{Power Consumption} = 4 \cdot I_{CS} \cdot V_{CE} + 3 \cdot I_{CS} \cdot V_{BE} + V_{BE}^2 / (R25 + R26) \qquad (7)$$

where I_{CS} indicates a current value of the constant current sources *CS11* to *CS17*.

In Eq. (7), the first term indicates the power consumption by the current from the constant current sources *CS11*, *CS12*, *CS16*, and *CS17*. The second term indicates the power consumption by the current from the constant current sources *CS13*, *CS14*, and *CS15*. The third term indicates the power consumption by the

output voltage Vo (V_{BE}(T16)) when the transistor $T12$ is turned off.

If Vb = 14V, V_{BE} = 0.7V, V_{CE} = 0.05V, $R25$ = 1kΩ, $R26$ = 100kΩ, and I_{CS} = 50μA which are suitable values in circuit design, the current consumption and the power consumption determined by Eqs. (6) and (7) will be 0.35mA and 0.12mW.

(b) Drive Circuit 1

The current and power consumptions in the drive circuit 1 are given by Eqs. (8) and (9) below.

$$\text{Current Consumption} = I_{CS} + (Vb - V_{BE}(T2) - V_{BE}(T4)) / R4 + (Vb - V_{BE}(T2) - V_{CE}(T4)) / R6 \quad (8)$$

$$\text{Power Consumption} = I_{CS} \cdot V_{CE}(T3) + Vb \cdot (Vb - V_{BE}(T2) - V_{BE}(T4)) / R4 + Vb \cdot (Vb - V_{BE}(T2) - V_{CE}(T4)) / R6 \quad (9)$$

If Vb = 14V, V_{BE} = 0.7V, V_{CE} = 0.05V, $R4$ = 24kΩ, $R6$ = 3.9kΩ, and I_{CS} = 50μA which are suitable values in circuit design, the current consumption and the power consumption determined by Eqs. (8) and (9) will be 3.97mA and 54.91mW.

Compared with the conventional drive circuit 1, the current consumption and the power consumption in the drive circuit 11 of this embodiment when the control signal Sa is in the H-level are decreased by 3.62mA and 54.79mW, respectively. This also results in a decrease in heat dissipation of the IC on which the drive circuit 11 is fabricated.

Additionally, compared with a circuit equivalent to the drive circuit 1 from which the voltage detector 20 and the comparator 20

are removed, the current and power consumptions in the drive circuit 11 when the control signal *Sa* is in the H-level are also decreased.

Figs. 3 and 4 illustrate the current consumption in the drive circuit 11 and the drive circuit 1 when the control signal *Sa* is changed from the H-level to the L-level and to the H-level, respectively. The abscissa axis indicates the time (μ s) The ordinate axis indicates the current consumption (A). The above described circuit design values are used. The graphs in Figs. 3 and 4 show that the current consumption in the drive circuit 11 during a time when the control signal *Sa* is in the H-level (i.e., between 0 to 10 μ s, 20 to 30 μ s) are decreased greatly as compared with that in the drive circuit 1.

When the control signal *Sa* is changed from the H-level to the L-level, the transistors *T11* and *T12* in the drive circuit 11 are both switched from the off-state to the on-state, so that no current flow through the transistors *T11* and *T12*. Specifically, at the instant the control signal *Sa* is changed from the H-level to the L-level, only a current charged in the MOSFET 14 flows out. The current consumption in the drive circuit 11 is, thus, a maximum of 0.1A which is smaller than a maximum of 0.24A in the drive circuit 1.

In the graph of Fig. 3, the current consumption increases slightly just after the control signal *Sa* is changed from the L-level to the H-level. This is because the time required for turning off the *pnp* transistor *T21* completely is relatively long, so that the current flows therethrough slightly even after the control signal *Sa* is

changed to the H-level. This problem may be alleviated by use of a high-speed transistor as the transistor *T21*.

As apparent from the above discussion, the driver circuit 11 of this embodiment has the high-side transistor *T11* and the low-side transistor *T12* connected in series across the output terminal 13 between the power supply line 16 and the ground line 17 and the predrivers 23 and 24 designed to supply a great base current to the transistors *T11* and *T12* for giving great current output abilities thereto. Specifically, the drive circuit 11 is capable of turning on the transistor *T11* through the predriver 23 to charge the gate capacitors of the MOSFET 14 connected to the output terminal 13 with a large quantity of current, thereby resulting in a decreased time required for turning on the MOSFET 14. The drive circuit 11 is also capable of turning on the transistor *T12* through the predriver 24 to remove a large quantity of electric charge from the gate capacitors of the MOSFET 14, thereby resulting in a decreased time required for tuning off the MOSFET 14.

The drive circuit 11 also includes the voltage detector 20 designed to detect the output voltage *Vo* (i.e., the gate voltage of the MOSFET 14) and the comparator 22 designed to compare the detected output voltage *Vo* with the off-decision voltage lower in level than the threshold value *Vth* of the MOSFET 14 and works to turn off the predriver 24 when the output voltage *Vo* is determined to be lower than the off-decision voltage to stop the supply of the base current to the transistor *T12*. Specifically, during a transitional period of time in which the MOSFET 14 is brought into the off-state,

the transistor *T12* is turned on, thereby causing the MOSFEZT 14 to be turned off quickly. After the MOSFET 14 is turned off, the current flowing through the predriver 24 (including the base current of the transistor T12) is cut, thus resulting in a decrease in consumption of current and power in the drive circuit 11. As compared with the conventional drive circuit 1, the heat dissipation from the IC on which the drive circuit 11 is fabricated is decreased greatly without increasing the turning-on time as well as the turning-off time of the MOSFET 14. This allows the drive circuit 11 to be used in a high temperature environment and a large number of drive circuits equivalent to the drive circuit 11 to be built in an IC.

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In the drive circuit 11, the longer the time in which the MOSFET 14 is in the off-state, the greater will be the current and power consumptions. The resistors *R25* and *R26* making up the voltage detector 20 work as pull-down resistors acing on the gate of the MOSFET 14. Therefore, even when the transistors *T11* and *T12* are turned off, the MOSFET 14 is kept off stably.

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Figs. 5 and 6 show a drive circuit 25 according to the second embodiment of the invention. For example, six drive circuits each equivalent to the drive circuit 25 are, like the first embodiment, fabricated in an IC as a six-channel driver and used in engine control for automotive vehicles.

The drive circuit 11 of the first embodiment is designed to reduce the power consumption when the *n*-channel MOSFET 14 is in the off-state, while the drive circuit 25 of this embodiment is designed to reduce the power consumption when a *p*-channel

MOSFET is in the off-state. The same reference numbers as employed in the first embodiment refer to the same parts, and explanation thereof in detail will be omitted here.

To the output terminal 13 of the IC on which the drive circuit 25 is fabricated, a *p*-channel MOSFET 26 is connected at a gate thereof. The MOSFET 26 is connected at a drain thereof to an electric load such as a solenoid (not shown) and at a source thereof to a power supply line 27 leading to the positive terminal of the battery. The MOSFET 26 has, like the first embodiment, gate capacitors *Cgs* and *Cgd*, as shown by broken lines.

The drive circuit 25 includes an output control circuit 28 for driving the transistor *T11*, an output control circuit 29 for driving the transistor *T12*, and a voltage detector 30. The voltage detector 30 is connected between the output terminal 13 and the power supply line 16 to detect the output voltage *Vo* appearing at the output terminal 13. The transistor *T11* and the output control circuit 28 function as a high side switching circuit. The transistor *T12* and the output control circuit 29 function as a low side switching circuit. In following discussion, the potential at the power supply line 16 will be defined as a reference potential for expressing the output voltage *Vo*, and potential levels below that at the power supply line 16 will be expressed in positive values.

The output control circuit 29 includes, as shown in Fig. 5, a comparator 32 and a logic circuit 31. The comparator 32 consists of a constant current source *CS18* and an *npn* transistor *T29* serving as a decision transistor. A resistor *R28* is connected between a

base and an emitter of the transistor *T29*. The logic circuit 31 has the transistor *T20* and the transistor *T28* connected in parallel. The transistor *T28* is coupled at a base thereof to a collector of the transistor *T29*.

The voltage detector 30 consists of a voltage divider made up of resistors *R29* and *R30* connected in series between the output terminal 13 and the power supply line 16, a *pnp* transistor *T27* connected at an emitter to the power supply line 16, and a resistor *R31* connected between a base of the transistor *T27* and a junction of the resistors *R29* and *R30*. The transistor *T27* is connected at a base thereof to a base of the transistor *T29* through the resistor *R32*.

The operation of the drive circuit 25 when the control signal *Sa* is changed in level will be described below.

(1) When the control signal *Sa* is changed from the H-level to the L-level

A change in level of the control signal *Sa* from the H-level to the L-level causes the transistor *T13* to be turned off, the transistors *T14*, *T17*, and *T18* to be turned on, and the transistors *T19* and *T20* to be turned off. This causes, on the low side, the transistor *T25* to be turned off, the transistor *T26* to be turned on, and the transistors *T24* and *T12* to be turned off. The collector voltage of the transistors *T20* and *T28*, i.e., the on-off state of the transistors *T22* and *T11* on the high side depends upon the level of the output voltage *Vo*.

Specifically, during a time when the output voltage *Vo* meets a relation, as shown below, after the control signal *Sa* is decreased to

the L-level, the transistors *T27* and *T29* are in the on-state, so that the transistor *T28* is in the off-state.

$$Vo \geqq (R29 + R30) / R30 \cdot Vf \qquad (10)$$

During the above time period, the collector of the transistors *T20* and *T28* is in the H-level, thereby causing the transistor *T22* to be turned on, the transistor *T23* to be turned off, and the transistors *T21* and *T11* to be turned on.

Thus, the drive circuit 25 discharges the electric charge on the gate capacitors of the MOSFET 26 to the power supply line 16 through the output terminal 13 and the transistor *T11*. This causes the output voltage *Vo* to decrease. When the output voltage *Vo* drops below the threshold value *Vth* of the MOSFET 26, it will cause the MOSFET 26 to be turned off.

After the MOSFET 26 is turned off, when the output voltage *Vo* drops further and meets a relation, as shown below, it will cause the transistors *T27* and *T29* to be turned off, so that the transistor *T28* is turned on.

$$Vo < (R29 + R30) / R30 \cdot Vf \qquad (11)$$

Note that the voltage level defined by the right side of Eq. (4) is the level of an off-decision voltage which is set lower than the threshold value *Vth* of the MOSFET 26.

When the transistor *T29* is turned off (i.e., the transistor *T28*

is turned on), the transistor *T22* on the high side is changed from the on-state to the off-state, thus causing the transistors *T21* and *T11* to be changed from the on-state to the off-state. The resistors *R29* and *R30* making up the voltage detector 30 serve as pull-up resistors acting on the gate of the MOSFET 26.

(2) When the controls signal *Sa* is changed from the L-level to the H-level

A change in level of the control signal *Sa* from the L-level to the H-level causes the transistor *T13* to be turned on, the transistors *T14, T17,* and *T18* to be turned off, and the transistors *T19* and *T20* to be turned on. The turning on of the transistor *R20* causes the collector potential of the transistors *T19* and *T20* to be in the L-level regardless of the level of the output voltage *Vp* detected by the voltage detector 30. This causes, on the high side, the transistor *T22* to be turned off, the transistor *T23* to be turned on, and the transistors *T21* and *T11* to be turned off, while, on the low side, it causes the transistor *T25* to be turned on, the transistor *T26* to be turned off, and the transistors *T24* and *T12* to be turned on. When the output voltage *Vo* exceeds the threshold value *Vth* of the MOSFET 26, the MOSFET 26 is turned on.

As apparent from the above discussion, the driver circuit 25 of the second embodiment has the voltage detector 30 designed to detect a potential difference between the power supply line 16 and the output terminal 13 (i.e., the output voltage *Vo* defined based on the potential at the power supply line 16) and the comparator 32 designed to compare the detected output voltage *Vo* with the

off-decision voltage lower in level than the threshold value *Vth* of the MOSFET 26 and works to turn off the predriver 23 when the output voltage *Vo* is determined to be lower than the off-decision voltage to stop the supply of the base current to the transistor *T11*. Specifically, during a transitional period of time in which the MOSFET 26 is brought into the off-state, the transistor *T11* is turned on, thereby bringing the MOSFEZT 26 into the off-state quickly. After the MOSFET 26 is turned off, the current flowing through the predriver 23 (including the base current of the transistor T11) is cut, thus resulting in a decrease in consumption of current and power in the drive circuit 25. The longer the time in which the MOSFET 26 is in the off-state, the greater will be the current and power consumptions.

Fig. 7 shows a drive circuit 33 according to the third embodiment of the invention. The same reference numbers as employed in Figs. 2 and 6 will refer to the same parts, and explanation thereof in detail will be omitted here.

The drive circuit 33 is designed to drive an *n*-channel MOSFET 14 and has a structure equivalent to a combination of those in Figs. 2 and 6. Specifically, the output control circuit 34 for driving the transistor *T11* has a structure consisting of components of the output control circuits 18 and 28.

The drive circuit 33 also includes the voltage detectors 20 and 30. In this embodiment, the voltage level determined by the right side of Eqs. (10) and (11) is the level of an on-decision voltage which lies within a voltage range in which the MOSFET 14 is turned

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Therefore, when the control signal *Sa* is changed in level for turning on the MOSFEET 14, the drive circuit 33 turns on the transistor *T11* on the high side. Alternatively, when the control signal *Sa* is changed in level for turning off the MOSFET 14, the drive circuit 33 turns on the transistor *T12* on the low side. This charges or discharges the gate capacitors of the MOSFET 14 quickly.

In a steady state after the MOSFET 14 is turned on or off, the predrivers 34 and 35 are both turned off to cut the supply of the base current to the transistors *T11* and *T12*, which results in decreases in current and power consumption of the drive circuit 33 regardless of an operational pattern of the MOSFET 14 (i.e., an on state-to-off state ratio), thus lowering the heat dissipation of the IC on which the drive circuit 33 is fabricated further as compared with the drive circuit 11.

Fig. 8 shows a comparator 36 which may be used instead of the comparator 22, as shown in Fig. 1, consisting the constant current source *CS13* and the *npn* transistor *T16*. The comparator 36 is connected at an inverting input to a junction of the resistors *R25* and *R26* making up the voltage divider and at a non-inverting input to a constant voltage *Vc* equivalent to the off-decision voltage as described above. The comparator 36 is also connected at an output to the base of the transistor *T15* shown in Fig. 1.

With the above arrangements, it is possible to change the off-decision voltage *Vc* directly without changing a fraction of the total voltage across the voltage divider appearing at the intermediate

tap or junction of the resistors *R25* and *R26*. As compared with a case where the base-emitter voltage *Vf* of the transistor *T16* is used as a reference voltage, the accuracy of voltage comparison is improved.

A drive circuit according to the fourth embodiment will be described below which is a modification of the one in the second embodiment.

Specifically, the drive circuit of this embodiment is identical in structure with the drive circuit 25 as shown in Figs. 5 and 6, but designed to drive the *n*-channel MOSFET 14 instead of the MOSFET 26, that is, to reduce the current and power consumption thereof when the MOSFET 14 is in the on-state.

In operation, the voltage detector 30 detects the output voltage *Vo* appearing at the output terminal 13. When the output voltage *Vo* exceeds an on-decision voltage which is determined by the right side of Eq. (11) lying within a voltage range in which the MOSFET 14 is turned on., the drive circuit turns off a high-side switching circuit consisting of the transistors *T11, T21,* and *T22* and the resistors *R18* and *R19*. This results in great decreases in current and power consumption, especially when the *n*-channel MOSFET 14 is kept on for a long period of time.

Other operations of the drive circuit are identical with those in the drive circuit 25, and explanation thereof in detail will be omitted here.

While the present invention has been disclosed in terms of the preferred embodiments in order to facilitate better

understanding thereof, it should be appreciated that the invention can be embodied in various ways without departing from the principle of the invention. Therefore, the invention should be understood to include all possible embodiments and modifications to the shown embodiments witch can be embodied without departing from the principle of the invention as set forth in the appended claims.

For example, each of the drive circuits 11, 25, and 33 may be used for driving a switching element such as a bipolar transistor or an IGBT. The switching element driven by each of the drive circuits 11, 25, and 33 may be of a *p*-type, an *n*-type, a *pnp*-type, or an *npn*-type. Each of the drive circuits 11, 25 ,and 33 may alternatively be made up of MOSFETs.

In the third embodiment, one of the voltage detectors 20 and 30, e.g., the voltage detector 30 may be omitted. In this case, the output control circuits 34 and 35 are designed to perform a comparison operation, logic operations, and predriver controlling operations based on the voltage Vp detected by the voltage detector 20.